Long-Term Visual Light Curves and the Role of Visual Observations in Modern Astrophysics

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Abstract Thanks to organizations such as the AAVSO, visual observations of variable stars have scientific strengths: they are numerous, sustained, and standardized. Though many people have predicted the demise of visual observation, the demand for such observations increased dramatically in the last quarter of the 20th century. In addition to their value in detecting, timing, and studying outbursts in CVs, fadings in R CrB stars, and eclipses in binaries, they are uniquely useful in studying the behavior of pulsating stars, especially slow, irregular, and long-term behavior, and changes in period and amplitude. In this review, I give a general review of this topic, with some emphasis on my own work on pulsating red and yellow variables, and on T Tauri stars. Much of this work has been done by undergraduate students and outstanding high school students; I highlight the importance and potential of AAVSO visual data for educational use.

1. Introduction

AAVSO observers have accumulated over 13.7 million visual measurements of variable stars in the last 100 years. Indeed, earlier visual and photographic measurements are now being digitized, so that the AAVSO International Database (AID) is being extended *backward* as well as forward. The AID is a unique resource for studying the long-term behavior of variable stars. For many stars, observations are made on an almost daily basis, often by multiple observers, so the datasets are often also dense and continuous.

Furthermore: the AAVSO has endeavored to maintain uniform sequences and magnitudes of comparison stars over time, so the measurements are stable over time. From time to time, however, the AAVSO and other variable star observing groups have noted that their comparison star sequences and magnitudes differed. Also: photoelectric V magnitudes are now available for most comparison stars. In the first decade of the 21st century, the AAVSO embarked on a massive project to create the best possible set of charts and comparison star sequences, and make them available on-line.

2. Long-term visual light curves

For stars in the AID for which the datasets are long and dense, the light curve shows the behavior of the star on time scales from days to decades. This is important for classifying the star, and for noting novel or unusual behavior, as well as for discovering and studying long-term variability which would not be evident in shorter datasets. I remember when the AID first became digitized, and it was possible to plot long term light curves of variable stars. I was especially interested in yellow supergiants at the time, and was excited to see the long term light curve of the RV Tauri star U Mon. It was known to have a long secondary period of about 2,500 days; hence it is classified as an RVB star. The AID light curve clearly showed multiple minima, separated by 2,500 days, which were reminiscent of an eclipsing binary. It is now generally accepted that most/all RVB stars are binaries containing a dust ring or torus which periodically eclipses the star (e.g. Van Winckel *et al.* 1999).

Individual visual observations, from an ensemble of observers, have an average typical accuracy of 0.25 magnitude, as determined by self-correlation analysis (e.g. Percy and Terziev 2011 and many other similar studies). An individual experienced observer, with a good chart and sequence, can probably achieve better than 0.1 magnitude accuracy if the sequence is given to hundredths of a magnitude, and if they are not rounding to the nearest tenth of a magnitude; a group of observers using the same chart and equipment, and under the same sky conditions, is also probably good to 0.1 magnitude (Templeton 2011a).

If the observations are sufficiently dense, and if the time scale of the variability is sufficiently long, then the observations can be binned in, for example, 30-day means whose accuracy is much higher—sometimes approaching photoelectric accuracy. This approach has been used to delineate the variability of stars such as ρ Cas, with a period of about a year and a small amplitude (Percy *et al.* 1985).

3. Timing semi-predictable minima and maxima

The AAVSO has a long history of timing the minima of eclipsing variables, and the maxima of RR Lyrae stars. In these cases, the stars are sufficiently periodic to predict the *approximate* time of minimum or maximum. The observer monitors the star for a short interval around the predicted time, and is more-or-less assured of being rewarded. The precise time can be determined from the observations, using Hertzsprung's method or the tracing-paper method.

Of course: if the time was *perfectly* predictable, there would be no need to observe the star, but both types of stars show period changes. Also, the observations can be used to refine the value of the period, even if the period is constant.

In eclipsing variables, period changes are generally due to mass transfer or loss in the system. Uniform mass loss causes O–C (observed minus predicted or calculated time of minimum) to vary parabolically with time. Stars with non-parabolic (O–C) behavior are of special interest, since the cause of the period change is less obvious.

In RR Lyrae stars, the period changes are generally due to evolution. The slow evolutionary expansion or contraction of the star, if uniform, produces parabolic (O–C) behavior. However, the observed rates of period change seem to be greater than those predicted by evolutionary models and, in some stars, the behavior is distinctly non-parabolic (Smith 1995). Long term period changes in RRab stars (which are pulsating in the fundamental mode, and have maxima which are sharp and easy to measure) have recently been determined by Le Borgne *et al.* (2007). RRc stars, which are pulsating in the first overtone mode, and have maxima which are flatter and harder to measure, have been less well-studied. My students are currently working on some of these.

Visual timing of these minima and maxima is gradually being replaced by CCD observations, but the visual observations, stretching back for many decades, are essential for measuring rates of period change. The accuracy of these increases as the *square* of the length of the dataset.

Cepheid variables are arguably the most important pulsating variables, because of their use in distance determination, and because their period changes can be directly and effectively compared with evolutionary models. This work is almost exclusively done with photoelectric photometry; visual observations have played and probably will play a minor role (Turner 2012, this volume).

In Mira stars, the (O–C) behavior is dominated by the effects of random cycle-to-cycle period *fluctuations*, first studied by Eddington and Plakidis (1929). Such fluctuations are also found in RV Tauri stars, a few long period Cepheids, and at least one W Virginis star; see Turner *et al.* (2009) for a brief review.

In the 1980s, Petrusia Kowalsky, Janet Mattei, and I, with support from the J.P. Bickell Foundation, carried out a study of seventy-five years of visual data on almost 400 Mira stars. We measured the cycle-to-cycle period fluctuations; they typically averaged a few percent of a cycle (Percy and Colivas 1999). A very few stars showed large period changes which were due to rapid evolution; these have been studied in more detail by Templeton *et al.* (2005). Beneath these random changes, however, we were able to detect the slow evolution of the ensemble of stars, at least at the 2σ level (Percy and Au 1999).

Professional astronomers often need to know the visual brightness or phase of a variable star at the time when they make observations using other techniques or at other wavelengths. If the star is strictly periodic, this is straightforward. If the star is irregular, it is not, but AAVSO monitoring can help. As one example: the European Space Agency *Hipparcos* mission observed Mira stars in order to measure their parallax, but the magnitudes of the stars, when observed, had to be optimal. AAVSO observers monitored a large sample of target Mira stars continuously, providing the *Hipparcos* team with the necessary magnitude data (Menessier *et al.* 1992).

4. Observing unpredictable maxima and minima

One of the most important contributions of AAVSO visual observers to modern astrophysics has been in monitoring and reporting outbursts in dwarf novae, recurrent novae, and novae. These result from mass transfer in a close binary system consisting of a normal star and a white dwarf or neutron star. When an outburst occurs, astronomers can quickly mobilize ground-based and space telescopes to study the outburst and its mechanism. AAVSO observers also monitor the visual variability of the star during outburst, for comparison with other data. This work is so important and interesting that there is a separate paper on it in this volume, by Paula Szkody.

Unpredictable *minima* occur in R Coronae Borealis stars—hydrogen-deficient, carbon-rich stars which occasionally eject a cloud of sooty dust which obscures and dims the star. These are rare objects; only a few dozen are known in the Milky Way and nearby galaxies. AAVSO observers monitor these and, when a fading begins, notify professional astronomers who can use a variety of techniques and facilities to study the progress and nature of the fading.

The times of onset of the fadings serve another purpose: it has gradually been realized (Crause *et al.* 2007) that, in many or most of these stars, the onset of fading is "locked" to a pulsation period in the star. This implies that the ejection of the cloud may be caused by the pulsation. The times therefore contribute to our understanding of the *cause* of the R CrB phenomenon. In a few stars (notably RY Sgr: Figure 1), the pulsation is large enough to be studied using visual observations; one of my students is currently studying the long term systematics of the pulsation in this star.

5. Period analysis of variable stars

For decades, the AAVSO's "bread and butter" was observing Mira stars. These are large-amplitude pulsating red giants. From this came periods and amplitudes in hundreds of Mira stars. Both the periods and amplitudes are notoriously variable, and the importance of studying these variations has only recently been appreciated.

For periodic variables, *time-series analysis* (Templeton 2004) provides information about the periods and amplitudes, and their changes. Fourier analysis of visual observations of semiregular (SR) pulsating red giants (Kiss *et al.* 1999) reveals multiple periods, representing multiple pulsation modes, and also "long secondary periods" (LSPs) whose nature and cause is still not understood. Wavelet analysis of AAVSO Mira star data reveals a small fraction of stars whose periods are changing due to the rapid evolution of the star (Templeton *et al.* 2005; Templeton 2011b).

Smaller-amplitude pulsating red giants are normally observed photoelectrically; indeed, most of the stars on the AAVSO Photoelectric

Photometry (PEP) program are stars of this type. Visual observations of these stars can, however, yield pulsation periods and LSPs (Percy *et al.* 1993), as long as the periods are reasonably coherent and the dataset is sufficiently dense and long.

One of the best examples of the power of visual observations is the study by Kiss *et al.* (2006) of pulsating red supergiants. They studied forty-eight SRc and Lc stars, using visual observations from the AID. The mean time-span of the data was sixty-one years. They found pulsation periods, typically hundreds of days in length, in most of the stars. Eighteen stars showed multiple pulsation periods. In some of these cases, there was a long secondary period, similar to the LSPs found in about a third of pulsating red giants. From the Lorentzian shape of the individual power spectra, they deduced the presence of period "noise," which they ascribe to interplay between pulsation and convection. Thus in this study, visual observations revealed fundamental properties of the stars (pulsation periods), an astrophysical mystery (LSPs), and clues to the physical processes (convection) going on in the stars. There may be useful astrophysical information in the detailed power spectra of other kinds of stars in long term datasets in the AID.

An interesting case, from my own research, involved T Tauri stars—sunlike stars in the process of formation. They vary, usually irregularly, on many time scales, mostly due to variations in the rate of accretion of gas onto the star. But the stars are also rapidly rotating, and have non-uniform surfaces, so may also be rotating variables with coherent periods of a few days, which are their rotation periods.

Back in the 1970s, some AAVSO visual observers began observing these stars. They tend to occur in specific star-forming regions, so they can be observed very efficiently. The observers were able to make many thousand observations of them each year, and thus rank high on the annual lists of top observers. Finally, Director Janet Mattei declared that visual observations of T Tauri stars would be devalued by a factor of ten in the annual observer totals. The observations languished, unvalidated.

I was able to convince AAVSO staff to validate the observations of a few well-observed stars, as a pilot project, and my student Rohan Palaniappan (a high school student at the time) analyzed them (Percy and Palaniappan 2006). Using Fourier analysis, he was able to detect and measure the rotational periods with amplitudes of only about 0.03 mag in the visual data!

6. Irregularity

A large fraction of all stars in the AID are classified as irregular, often because there are insufficient observations to characterize the behavior of the star more fully. As one example: RV Tauri stars are defined as pulsating yellow supergiants showing alternating deep and shallow minima; SRd stars are irregular pulsating yellow supergiants. Detailed analysis of AAVSO visual observations of these stars shows that there is a smooth continuum of behavior from RV Tauri to SRd. There is even a link to W Virginis stars, in that some of these show a slight alternation between deep and shallow minima.

As mentioned above: many of the semiregular pulsating red giants (SR stars) are multiperiodic. My students and I have just completed a study of visual observations of several dozen red giants in the AID which have 250 or more observations, and which are classified as *irregular* (L type stars) (Percy and Terziev 2011). Their amplitudes are a few tenths of a mag in only a few stars; many/most are microvariable; quite a few are or probably are non-variable. A very few have a detectable period. Most of these stars are candidates for photoelectric observations, but the scientific value of such observations is not clear.

In pulsating yellow supergiants such as RV Tauri and SRd stars, there is strong evidence that the irregularity is a consequence of dynamical chaos. The same physical principles which produce coherent pulsation in dense, compact stars produce irregular pulsation in more distended stars. Theoretical studies have been made by Toshiki Aikawa, Robert Buchler, Zoltan Kollath, Geza Kovacs, Pawel Moskalik, Mine Takeuti, and their colleagues, and compared with long term AID light curves of Miras, RV Tauri, and SRd stars.

7. Other applications of visual observations

There are many other applications of visual observations, some of which are described elsewhere in this volume:

- Visual discovery and study of supernovae: observers such as Robert Evans in Australia have discovered dozens of supernovae in relatively nearby galaxies; these are very useful for calibrating supernovae as “standard candles” for cosmological purposes.

- Monitoring hypergiants such as P Cygni and ρ Cas for outbursts or other unusual behavior.

- Visual monitoring of T Tauri stars for slow, long term variations which are usually due to variations in their rate of mass accretion.

- Visual monitoring of symbiotic stars—close binaries with a cool giant component and a hot normal or compact star: these undergo eruptions, eclipses, and, in some cases, pulsation.

- Although visual observation of small-amplitude variables is not usually recommended, there are a few observers who, given the right star and the right circumstances, can achieve a visual accuracy of a few hundredths of a magnitude. A notable example is the study by Otero (2011) of the Be star δ Sco.

8. Educational considerations

The AID is a wonderful treasure chest of publicly-available scientific data which can be used by high school and university students to develop and integrate their science, math, and computing skills. Some of the data have never been fully analyzed; by analyzing these data, students can be motivated by the thrill of doing real science research. I have co-authored dozens of papers and presentations with undergraduate research students, and with outstanding senior high school students in the University of Toronto Mentorship Program (Percy *et al.* 2008). This educational potential was recognized early on by me and the late Janet Mattei; it led to the AAVSO's *Hands-On Astrophysics* (Mattei *et al.* 1996) which has evolved into *Variable Star Astronomy* (www.aavso.org/education/vsa).

Students can also observe bright stars (such as Mira and δ Cep) visually, just as the first variable star astronomers did centuries ago. In the case of δ Cep, they can tie their observations of the time of maximum brightness with those of John Goodricke and Edward Pigott in the 18th century, and actually detect the evolution of this star. There is great interest, among historians of science, in re-creating the key observations and experiments in the history of science.

9. Final reflections

Are visual observations obsolete? This is a question which has been asked for over three decades. In the first twenty-five years of "the space age" (the last twenty-five years of the 20th century), however, the demand for visual observations *increased* by a factor of 25, due to the rise of high-energy astrophysics (Szkody 2012, this volume). In 2011, the question is driven by the fact that visual observations now represent a small fraction of all the observations submitted to the AID, and by the impending advent of massive nightly robotic surveys of the sky. A slightly different driver is the fact that so many long-time visual observers are retiring, but this factor is more related to the "greying" of amateur astronomy; we must recruit more younger people to amateur astronomy, and variable star observing. And we must recruit both men and women, of all races and backgrounds. The popularity of projects such as *Galaxy Zoo* suggests that there are many thousands of untapped "citizen astronomers" out there.

My personal view is that visual observations can still play an important role, but it would help if the AAVSO provided stronger guidance, and if observers were willing to take it. Observers need a certain amount of flexibility and freedom, but they probably don't want to think that their observations are of little scientific value. Through a combination of training, motivation, and feedback, we can provide observers with the assurance that their observations are continuing to contribute to science.

Users of AAVSO data, such as myself, have a responsibility here; that's why my students and I like to use AAVSO data and to present our results at AAVSO meetings, and publish them in *The Journal of the AAVSO*. The newly-formed observing sections can also play a role in guiding the observing programs so that they are maximally effective. Formal reviews of the AAVSO observing programs, by either internal or external reviewers, could be carried out every few years. Those of us with research grants have our observing plans reviewed every time we apply to renew our grants!

Even if robotic sky surveys were to provide complete coverage of the sky currently performed by visual observers alone, existing and future visual observations (and the backward extension mentioned in the first paragraph) would continue to be useful because, for many purposes, the usefulness of a light curve increases with its length. It would therefore be important to be able to "match" the visual data to data from these surveys.

I would like to think that visual observations of variable stars will continue to be useful for decades to come—if only because there is a special joy in having the human eye and brain come in direct contact with the cosmos.

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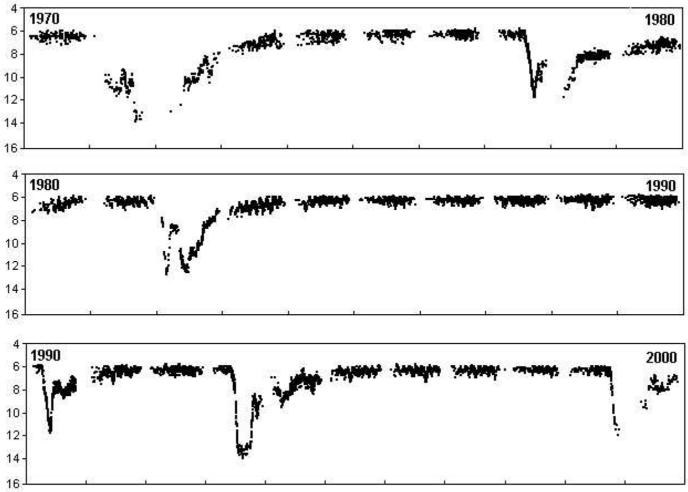

Figure 1. AAVSO thirty-year visual light curve of the R CrB star RY Sgr. The fadings, and their onsets, are clearly visible. The small-amplitude 40-day pulsational variability is also visible as a "sawtooth" when the star is at maximum.